University of New Brunswick Fire Science Centre

Evaluation of "Modelling the Response of an LPG Carrying Rail Tank Car to an External Fire Environment" by Davis Engineering Ltd.

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17. Abstract

This report documents the evaluation of "Modelling the Response of an LPG Carrying Rail Tank Car to an External Fire Environment" (Davis Engineering Ltd., TP 3987E, October 1982) which develops mathematical model of heat transfer processes in an LPG carrying rail tank car exposed to a fire environment. The proposed model is intended for use in the analysis of the results of experimental tests of a tank car protective system and in the development of alternative designs of the protective system.

The evaluation was carried out by critically reviewing and assessing the following main areas of interest: problem physics, assumptions, initial and boundary conditions, mathematical formulation, and proposed numerical methods. The feasibility of the proposed approach for the remaining work phases and the completeness of the report are also assessed.

It is concluded that the proposed study approach appears reasonable and that the proposed methods and models along with the boundary conditions offer a practicable numerical scheme to predict the response of a tank car with a variety of exterior and interior protection devices.

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17. Resume

Ce rapport évalue l'étude intitulée "Modelling the Response of an LPG Carrying Rail Tank Car to an External Fire Environment", (par Davis Engineering Ltd., TP 3987E, octobre 1982) qui proposait un modèle mathématique des flux thermiques à l'intérieur d'un wagon-citerne transportant du gaz de pétrole liquifié et pris dans une conflagration. Cette modélisation doit servir à l'analyse des résultats des essais d'un système nouveau de protection des wagons-citernes et aussi à la mise au point de configurations nouvelles dudit système.

L'évaluation se fonde sur une analyse critique des points suivants: caractérisation physique du problème, hypothèses de départ, conditions initiales et aux limites, formulation mathématique et méthode de résolution numérique. Elle porte également sur la faisabilité des phases à venir de l'étude, en plus de considérer dans quelle mesure cette dernière fait le tour de la question.

Le rapport conclut que la voie proposée pour l'étude semble raisonnablement fondée et que la méthodologie et les modèles mathématiques mis de l'avant offrent, compte tenu des conditions limites proposées, une bonne possibilité de résolution numérique des équations de flux thermiques dans un wagon-citerne équipé de protections diverses tant à l'extérieur qu'à l'intérieur.

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Summary

Under the terms of agreement for the service contract No. 4710, dated 22nd of March 1982, the University of New Brunswick Fire Science Centre has carried out the evaluation of the draft report entitled "Modelling the Response of an LPG Carrying Rail Tank Car to an External Fire Environment" dated October, 1982, by Davis Engineering Limited.

This project is performed as part of the Tank Car Explosion Protection Program - Phase I, which has the primary objective of developing a mathematical model of heat transfer modes in a rail tank car under fire conditions.

Davis Engineering Ltd. have reviewed the 1/5 and full scale tests reported by Canadian and U.S. investigators. Their explanation of the observed sequence of events, specifically as they relate to the results of Anderson et al [1] and TP2740 [2] omit two key factors, namely the role of the PRV flare on external radiation heat transfer and the PRV temperature-time action on pressure response. The role of ethane in initial vapour superheat and liquid overpressure during initial phases appears possible.

The boundary conditions external to the tank and propane are well researched and comprehensively justified. However, some of their assumptions are questionable. In particular the assumption of a transparent gas model for the ullage space complicates the treatment of radiation heat loss from the tank wall. Also the treatment of the effective thermal conductivity of the Propane-EXPLOSAFE matrix neglects to include any effect in the liquid. The "swelling" of the liquid, due to bubble formation caused by homogeneous nucleation, and its effects on liquid surface area and apparent liquid inventory is not included. The treatment of geometry permits roll and pitch considerations.

Davis Engineering Ltd. have modelled the propane lading as a subcooled and stratified two region liquid and a single region vapour. An integrated form of the unsteady state energy equation is utilized - closed system representation with PRV closed and open system representation with PRV open. Thermal stratification effects are modelled empirically in the liquid. Both pool and torch models may be used together. Failure criteria are well treated and represent satisfactory and economical considerations.

The model summary and proposed approach for the remainder of the work appears reasonable.

It is concluded that the proposed methods and models along with the boundary conditions offer a viable numerical scheme to predict the tank car response for a variety of external and interior protection devices.

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References

1. Introduction

This document reports the evaluation of the draft report entitled "Modelling the Response of an LPG Carrying Rail Tank Car to an External Fire Environment" dated October 1982, by Davis Engineering Ltd.

The objectives of the evaluation are to:

i) Study the report in order to become familiar with the approach taken by the contractors and

ii) evaluate the report with respect to problem physics, assumptions, initial and boundary conditions, mathematical formulation, proposed numerical methods, proposed approach for the remaining phases, and completeness.

The evaluation was prepared by Dr's. J.G. Lenard, A.C.M. Sousa, F.R. Steward and J.E.S. Venart under the terms of the Transportation Development Centre (TDC) Service Contract No. 4710 dated March 22, 1982. In the following we describe in detail our evaluation of the Contractor's Report under the items listed above.

2. Problem Physics and Assumptions

The thermal models commence with a consideration of mathematical and numerical factors influencing a solution to the problems of torch and pool fire environments surrounding an LPG tank car. In many respects it is presumed that all the physics are known and that they can commence with the work of Graves [3], implement a refined treatment of geometry, boundary and internal conditions, include the effects of EXPLOSAFE in the ullage only, and obtain a superior analysis. The reviewers would prefer to have seen the physical problem described first along with the necessary assumptions that would lead to the mathematical and numerical models. The finite difference or any other mathematical method is only a solution tool. The contractor's method of approach leads

one to believe that the thermal phenomena may be modelled to suit the numerical scheme.

In their evaluation of numerical schemes, consideration should also have been given to the use of a stable and explicit scheme, for example the Dufort & Frankel scheme [4].

The statement concerning the role of EXPLOSAFE i.e. (p. 3, para. 2) "The high thermal conductivity of the EXPLOSAFE mesh enhances the conductivity of the vapour and allows the heat being transferred from the fire to the tank wall in the ullage to be dissipated to the liquid lading which boils off and is safely released through the relief valve provided the valve is adequately sized" is further evidence that little time has been spent on a consideration of problem physics. Since tank failure invariably occurs in the ullage, it is imperative to enhance the tank interior surface heat transfer; that is, rather than use a circumferential pack, i.e. Style II radially and Style III circumferentially, Style III should have been placed radially. The top shell temperatures reported in TP2740 for NOVA and ENIGMA indicate similar shell side temperatures at the end or termination of tests (approximately 1050°F). A radial pack would have presumably permitted lower vapour temperatures, due to conduction to the vapour and higher boiloff rates due to promotion of boiling in the liquid.

The detailed treatment of the numerical methods includes consideration of computer storage, linearization techniques, and time-integration methods applied to exterior and interior tank nodes. There is a comprehensive assessment and justification of many of the assumptions, for example the neglect of axial conduction. Concerning the N-R method there is not much to be commented, it is their choice. It should be noted, however that the use of IMSL library routines may lead to some minor problems:

i) "black box use"

ii) unavailability of IMSL library in a particular computing centre or changes on IMSL interface.

The fact that the Modified Newton-Raphson method requires that the 'N' parameter to be fixed "based on user's experience" (p.37) may hinder its more general applicability. It is recommended that N be an automatic selection made by the computer code.

The tank car geometry description and co-ordinate scheme developed will consider roll, PRV and other safety device placement, and pitch. The choice of cylindrical geometry is justified. The definition of "liquid surface" (p. 47), last para.) is unclear since with homogeneous boiling there is a two-phase region in what was the stratified surface layer of the liquid. In other words, there is an apparent "swelling" or expansion of the fluid which raises the "effective" liquid level and hence increases ullage convective heat transfer coefficients due to PRV action. This may also influence side wall transfer.

3. Initial and Boundary Conditions

In sections 2.3 to 2.5 the contractor's evaluate the various exterior and interior conditions influencing the proposed analysis.

The exterior boundary condition data for a pool fire, fire to tank, radiative (2.3.1.1) and fire to tank, convective (2.3.1.2), are evaluated and a justification made for the types, formulations and models, proposed. The model will be able to specify either a uniform or variable surrounding flame temperature. The fire and convective coefficients, h_f = 5∿15 W/m^2K, are justified on the basis of a comprehensive evaluation (Appendix C) using the work of Raj [5] and Russel and Canfield [6]. The contractors do not recognize the significance of the PRV flare radiation load.

Whether JP-4 fires can be used as a basis for all fires is certainly debatable (p.322, para. 2), while the flow pattern and entrainment pattern is probably similar, radiative transfer could be very different depending on soot formation in the flame.

This could also affect the temperature distribution in the fire. While the procedure for determining a heat transfer coefficient (p. 325) may be the best available from published data in the literature it should not be considered too reliable. The scale of turbulence in a pool fire is very much greater than that in the free stream of a wind tunnel.

While all the contractor's analysis is good, insofar as one wishes to obtain an approximate outside boundary condition it should not be regarded as more than this. For a first case model a single boundary condition should be used such as constant heat flux or heat flux varying with angle. If too many complicated analyses are used throughout the model in the initial stages it will be impossible to determine which variable is affected by the result. In our opinion the concept of starting simple and adding complicating factors later is an important one.

In the evaluation of the unprotected Tank Car Thermal Analysis (2.3.2), the method of attack for determing the radiative heat transfer between the tank wall and the vapor surface is essentially correct, however, we are not sure that the conclusions are.

The calculations show that propane vapor will absorb virtually all radiation in the two strongly absorbing bands 3.3-3.6 μm and 6.5-7.7 μm. This absorption will occur over a very short distance, a fraction of a mm. However, assuming the remainder of the spectrum to be transparent is questionable, particularly above 7.7 μm. Although the absorption is much weaker, approximately 1/10 that of the strong bands, it will still absorb the radiation over the distance measured in some fraction of a meter. A black gas model is more appropriate and simpler since no interchange factors are necessary.

The convective heat transfer to propane vapour (2.3.2.3) will not model free convection in the ullage, forced convection,

due to PRV flow only will be considered. The arguments for the neglect of free convection do not appear strong and some quantitative assessment would have been desirable as some evaluation of the vapour thermal stratification appears necessary.

When the relief valve functions heat transfer will be by forced convection in the ullage (appendices D and E). Various configuration of valves are considered as well as the question of local cooling at PRV locations. It is considered that this latter effect is of minor importance. In our view however the major question here appears to be the fact that these estimates of heat transfer coefficients are lower bounds in that vapour velocity is a function of liquid level - two-phase "swelling" of the liquid will have an important effect and increase coefficients over those that are proposed (p. 81-90).

The statements (p.84) that describe the procedure (Appendix D) and indicate that full scale interior coefficients ($h_{if} \simeq 8$ W/m^2K) are approximately one half those of the fifth scale ($h_{i\ 1/5} \simeq 17$ W/m^2K) appear substantiated but leave unresolved the question as to why the full scale tests have less vapour superheating than the 1/5 scale tests despite their higher heat fluxes.

In 2.3.2.4 the heat transfer from the liquid wetted wall (p.93) is described. At the interface of the liquid surface the effect of the wall conduction results in a heat flux "spike"; again we must ask where is the liquid interface?

The statements "since wall heat fluxes measured are between 22 and 142 KW/m^2 it is quite apparent that the inner surface of the tank will not exceed the saturation temperature by more than 10-12°C" and "the critical heat flux (CHF) for vertical surfaces is generally less than CHF for horizontal surfaces (18)" are not supported by measurement [1,2] or other literature [7,8]. The effects of "swelling" and hence density differences on the formation and accelerating or decelerating movement of vapour in the wall region is not considered; the local coefficients may be higher or lower than that proposed by Graves [3]. The effect of the

heat flux "spike" should thus be attenuated.

In section 3.2.2.5 the contractors describe the unprotected tank model details. The arguments (p.101) for not spending a large effort on radiation transfer between the shell and the liquid through the vapour space is valid up to a point. The transfer of heat from the shell to the liquid may not be important in heating up the liquid, it could possibly even be neglected entirely. However, the importance of radiative transfer from the shell as a heat loss mechanism may be quite important in determining whether the shell fails in the vapour section of the tank. Radiation becomes important when the tank is likely to fail.

The interchange factor (p. 104) could perhaps be obtained analytically without too much difficulty. It may be available. For an infinite cylinder it can be obtained by the crossed strings method. The equation 2-79 (p.104) is in fact rigorous using ℓ as the arc if the system is infinite. The relation breaks down as the cylinder becomes finite. However, as indicated above we believe it could be determined analytically.

The temperature of the tank wall at the liquid level is to be set at the temperature of the liquid for each time step in both the unprotected and EXPLOSAFE configurations; this results in a model for an ullage space defined in terms of a hypothetical liquid level which is incorrect. We do not anticipate that this will be successful in that the bulk of the heat transfer is to the liquid and hence errors in its evaluation result in serious errors in the heat transfer to the vapour space.

The EXPLOSAFE equipped tank car thermal analysis is described in sections 2.3.3. The contractors have performed adequate measurements and supporting evaluation of the thermal conductivity and radiation contributions of EXPLOSAFE/vapour matrices. The effect of EXPLOSAFE/liquid configurations is not considered. The model details (2.3.9) determine the

conduction effects on the vapour space coupled with a user specified turbulence multiplier for PRV forced convection. Radiation effects in the EXPLOSAFE are not modelled. The statement, (p. 158, 2nd para.) "the temperatures of the uppermost nodes in the liquid will be fixed at the liquid temperature and the rest of the nodes eliminated at each time step causing the fraction of the EXPLOSAFE annulus modelled to vary as the liquid level varies," presumes that the presence of EXPLOSAFE in the liquid does not affect the boiling characteristics and hence they may use the same liquid heat transfer coefficient as before. A comparison of the results between NOVA and ENIGMA [2] shows that there is a marked reduction in the peak sustained pressure (5-6 min) of about 30 - 40 psia in NOVA. Further, vapour superheating is substantially less at similar times (650°F vs 500°F for NOVA) possibly due to the difference in boiling characteristics. We have pointed out previously [9] that boiling in an expanded bed, such as EXPLOSAFE, results in much higher heat fluxes with typically lower temperature differences. Reference [10] can be used to estimate CHF effects with EXPLOSAFE. The propane properties should be obtained from Goodwin [11] rather than their proposed source (p. 161).

The evaluation and analysis of the torch fire is reasonable. The contractors have given a great deal of thought to this problem. Equations 2-100 and 2-101 are based upon results for torches "small" with respect to those anticipated for large accidents. Their evaluation of dryout conditions permits them to restrict attention to the effect of the flare on the vapour space only. We are in general agreement with this assessment, however the combined effect of a pool and torch fire condition, particularly a torch impinging just below the "liquid" level may necessitate re-evaluation of this conclusion.

4. Mathematical Formulation and Numerical Methods

The thermodynamic models are considered in section 3. With the PRV closed (3.1) with (3.1.2) and without EXPLOSAFE

(3.1.1) closed system representation of the unsteady energy equation is employed. Vapour superheat is neglected in both cases (p. 217 and 204 respectively) however the statement "the vapour will actually become slightly superheated near the tank wall but this effect can undoubtedly be ignored" requires some justification for the system without EXPLOSAFE as superheats greater than 100°F were reported in the 1/5 scale tests [2].

The evaluation that the pressure is set by the surface layer of the liquid may be true. Their evaluation that the 2-3% of Ethane impurity is totally responsible for the initial vapour superheat and liquid overpressure is perhaps overstated. The actual situation is probably a combination of effects. Davis Engineering recognizes that "thermal stratification in the liquid will be difficult to model" (p. 208). They do not propose to do this "until it has been demonstrated that thermal stratification of the liquid during early times has a significant effect on the time at which the car eventually ruptures." This argument is weak and out of character with respect to the caliber and quality of the majority of the report. The inclusion of a surface temperature gradient K=dT/ds (p. 209), is a fitting parameter. For unprotected tanks K is 7.3 K/m full scale and approximately 100 K/m 1/5 scale just prior to PRV vent. There are obvious scale effects and while we can evaluate K for 1/5 EXPLOSAFE tanks what values do we use for full scale design? The "K" parameter and the rate at which the integrated bulk liquid temperature increases are obviously going to be functions of the heat flux, geometry, and packing.

When the PRV is open (p. 221) with (3.2.2) and without EXPLOSAFE (3.2.1) requires a user specified fraction "f_q" of the total heat flow rate into the tank until the liquid becomes isothermal. Again this is another "fitting" parameter which should obviously be related to the "K" parameter utilized in the previous section. The question of scale effects must be considered.

In both these sections (2 and 3) there is an obvious difficulty in the heat transfer and thermodynamic models. On one hand the heat transfer analysis uses the liquid volume (height) to determine the material evaporated and the temperature distributions. The thermodynamic and heat transfer models are both bound by $V_L=V_T-V_V$ but the "true" heat transfer and evaporating surfaces will differ significantly from those proposed. Some estimate of liquid swelling may be required. A method such as proposed in Reference [12] may be considered.

The pressure relief valve model for liquid (3.3) and vapour (3.4) stagnation propose utilizing the work of Sallet [13]. Initial pressure relief valve functioning will depart substantially from those proposed for steady state operation by Sallet [13], Anderson et al [1] reports initial valve coefficients of approximately 0.4.

Tank rupture considerations under pool (4.1) and torch (4.4) fire situations are very comprehensive. Under pool fire conditions

- It is assumed that pressure induced stresses alone cause rupture;
- The possibility of rupture in the cylindrical portion only is considered;
- Stresses are to be calculated by assuming that the vessel is a thin-walled cylinder, loaded in an axially symmetrical manner;
- While the procedure described is a valid approach to estimate "time to rupture", we believe that the accuracy of the estimate cannot be established. There are many assumptions which limit the accuracy, even though good arguments are presented to defend those assumptions.

For a torch fire the contractors propose to follow the method described above. We believe that the results would not be very good, since no axial symmetry can now be assumed. Use of a finite element model in this case may be necessary.

A stress rupture based upon hoop stress will be utilized in both instances. The use of F.E. rupture analysis is considered in section 4.5, the contractors are cautious in recommending its use for all but the most important aspect of the failure analysis,due to cost.

The model summary (5.0) and its associated flow chart (pp. 287-290) appears to be complete and logical.

5. Proposed Approach for Remaining Phases

Section 6, Conclusion and Recommendations, summarizes the report and considers the effect of EXPLOSAFE on a BLEVE. It is concluded that the effect will be minimal. No experimental work to determine CHF and the effect of other heat transfer mechanisms, than considered by the contractors, is recommended until it has been demonstrated necessary. Stress-Rupture data for the steels used in tests will have to be obtained.

The Proposed Activity Schedule, Section 7.0 is well thought out and unambiguous.

6. Completeness

Aside from a lack of recognition of a few of the physical aspects of the problem the report is well prepared.

7. Conclusion

The report entitled "Modelling the Response of an LPG Carrying Rail Tank Car to an External Fire Environment" by Davis Engineering Ltd. has been reviewed and evaluated. It is concluded that the numerical models and methods proposed along with the proposed boundary conditions can be utilized in a numerical model to predict the tank car response for a variety of external and interior protection schemes.

1. "The Effects of a fire environment on a Rail Tank Car filled with LPG", FRA-OR&D 75-31, C. Anderson, W. Townsend, J. Zook, G. Cowgill, September 1974.

2. "Testing and Evaluation of the EXPLOSAFE system as a method of controlling the Boiling Liquid Expanding Vapour Explosion (BLEVE)" TP 2740, R.D. Appleyard, Dept. of Res. & Dev. EXPLOSAFE Div. of Vulcan Ind. Packaging Ltd., August, 1980.

3. Development of a computer program for the modelling of the heat effects on a railroad tank car "PB-241 365 R.W. Graves, Calspan Corp. FRA DOT-AR 20036 Jan. 1973.

4. Roache, P.J., Computational Fluid Dynamics, 1976, Hermosa Publishers, Albuquerque, N.M.

5. Raj, P.K., Analysis of JP-4 Fire Test Data and Development of a Simple Fire Model, ASME paper 81-HT-17, 10 pages.

6. Russell, L.H. and Canfield, J.A., Experimental Measurement of Heat Transfer to a Cylinder Immersed in a large Aviation-Fuel Fire, J. Heat Transfer, Aug. (1973), pp. 397-404.

7. Chen, L.T., Heat Transfer to Pool-boiling Freon from Inclined Heating Plates. Letters in Heat and Mass Transfer, 5, pp. 111-120 (1978).

8. Githinji, P.M. and Subersky, R.H., Some Effects of the Orientation of the Heating Surface in Nucleate Boiling, J. Heat Transfer, Nov. (1963), p. 379.

9. Venart, J.E.S, Comments at TDC Meeting with Contractor, Montreal, July 16, 1982.

10. Dhir, V.K., and Catton, I., Boiling in a Porous Bed. Applied Scientific Research, 38, pp. 66-76 (1982).

11. Goodwin, R.D., "Provisional Thermodynamic Functions of Propane from 85 to 700 K at Pressures to 700 Bar." NBSIR 77 - 860, July 1977, 239 p.

12. Singh, K.P. and Gupta, J.P., "Transient Swelling of Liquid Level During Pool Boiling in an Emergency Condenser", Letters in Heat and Mass Transfer, Vol. 8, 1981, pp. 25-33.

13. Sallet, D.W., "Twp-Phase Flow Aspects in Sizing Pressure Relief Valves", Safety Relief Valves, R.W. Haupt and R.A. Meyer, editors, ASME, PVP-33, New York, pp. 31-41, 1979.

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